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A Simplified Method for Seismic Analysis of Tanks with Floating Roof by using Finite Element Method: Case Study of Kharg (Southern Iran) Island Tanks

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Abstract

Tanks with floating roof have shown high vulnerability subjected to past earthquakes, such as Kobe, and Izmit. The main cause of damage is believed to be the interaction between the floating roof and the tank wall. In this paper a simplified method is presented for modeling the floating roof and its interaction with the tank wall, making it possible to use Finite Element Analysis (FEA) for calculating the seismic response of tank-floating roof system. In the proposed method, assuming that the sloshing phenomenon is mainly suppressed by the floating roof, the seal between the roof and the tank's wall is modeled by introducing some radial pre-compressed 'only-compression elements' all around the roof, itself substituted by a rigid disk, and the tank's wall is modeled by 3-dimensional shell elements. The dynamic effect of the impounded oil in the tank is taken into account by the use of added mass concept. If during the time history analysis the maximum relative displacement between the roof disk and the tank's wall in any radial direction exceeds the initial length of the pre-compressed only-compression springs the tank is considered to be vulnerable. The proposed method has been applied to a tank sample in Kharg (southern Iran) island.

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Keywords: Only-compression elements, Radial springs, Shell elements, Added mass

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1. Introduction

Tanks with floating roof are among the very common types of tanks used in the oil industries all over the world. However, this type of tanks has shown high vulnerability subjected to past earthquakes. Kobe, Japan earthquake of 1995 and Izmit, Turkey earthquake of 1999 are two of these events. The main cause of damage is believed to be the interaction between the floating roof and the tank wall, via the interfacing seal, leading to instantaneous separation between the roof and the tank wall, and resulting in the escape of the flammable oil gases to the free space.

Studies on the floating roof tanks subjected to earthquake go back to early 80s (Sekai et al. 1984), and has continued till recent years (Yoshida 2009). Sakai and his colleagues (1984) investigated the sloshing behavior of floating-roofed oil storage tanks through theoretical analysis and model testing. Their analysis employed theory of fluid-elastic vibration to study the interaction between a roof and the contained liquid. The finite element method was applied, in which a technique based on the variational principle of boundary integrals was used to simplify the solution. The theory was verified by shake table experiments with three large models of single deck type and double deck type of floating roofs. From those results they came to the following conclusions: 1) The existence of floating roofs hardly affects the first natural mode of sloshing, 2) The roof rigidity has important effects on the behavior of the higher modes, and the influence of the higher modes should be considered in determining stresses of double deck type floating roofs, and 3) The local deformation of the lower deck plays a great role on the sloshing behavior; in fact, in single deck type floating roofs the relative rigidity of roof is very low, and the existence of the roof can be ignored, however, in double deck type floating roofs, the global rigidity seems to be much higher and the local deformation of bottom plates has significant influence on the behavior, especially in the higher orders. Therefore, to get the more accurate values of natural frequency and of dynamic pressure, the double plate analysis should be applied, and finally, 5) For a tank with a floating roof, the experimental result shows that the higher mode responses are not so pronounced, and the apparent damping coefficients are estimated as 5-10%.

Shi and his colleagues (1986) by applying the elastic theory of shells and plates and the theory of hydroelasticity with the finite element technique-source distribution method analyzed the shell-liquid-plate coupling vibration. In recent decade more attention was paid to the floating-roof tanks. Following the occurrence of an earthquake in Hokkaido on September 2003, which resulted in not only failing and sinking the floating roofs, but also form fire in many tanks, Shimada (2005) tried to propose a solving prevention system for the floating roof type petroleum tanks. With regard to Hokkaido earthquake Sakai and his colleagues (2006) performed another study on the fluid-elastic analysis and design of sloshing in floating-roof tanks with special attention to the single-deck floating-roofs. Yamazaki and his colleagues (2006) also conducted a study on the seismic design of floating roof of oil storage tanks under liquid sloshing, claiming that bucking of the roof has been the main mode of failure. Yoshida (2009) specifically studied the buckling characteristics of floating roof pontoons in aboveground storage tanks subjected to both compressive and bending loads.

It is seen that in spite of some thorough studies on the sloshing phenomenon, still the separation between the floating roof and the tank wall, which is believed to be the main cause of fires in the past earthquakes has not been investigated in detail. In this paper a simplified method is presented for modeling the floating roof and its interaction with the tank wall, making possible to use Finite Element Analysis (FEA) for calculating the seismic response of tank-floating roof system. In the proposed method, regarding that the first mode of sloshing is not likely to happen, due to very large diameter of the considered tanks, it is assumed that the floating roof can suppress the higher modes of sloshing phenomenon. The proposed method has been applied to the large diameter tanks in Kharg (southern Iran) island, shown in Figure 1.

Figure 1: The large oil storage tanks in Kharg Island, considered in this study (compare the tank size with that of the soccer playground shown in the picture.)

2. Finite Element Modeling And Analysis Of The Tank System

For modeling the tank-roof-oil system, it is assumed that the sloshing modes other than the first mode, are suppressed by the floating roof. Regarding that the in-plane stiffness of the roof is much higher than the surrounding seal, the seal between the roof and the tank's wall is modeled by introducing some radial pre-compressed 'only-compression elements' all around the roof, and the roof is substituted by a rigid disk. The tank's wall is modeled by 3-dimensional shell elements, and the dynamic effect of the impounded oil in the tank is taken into account by the use of added mass concept (Epstein 1976).

The tank's diameter and height are respectively 109 m and 17 m, and its wall thickness is varying from 4 cm in the lower parts to 1.5 cm in the upper parts. The maximum depth of oil in the tank is 15 m. Tank's wall is modeled by shell elements of 1.4 m dimension, being fixed at the bottom of the tank. The seal has been substituted by 18 equally spaced (at 5 degrees) only-compression springs placed in radial direction, each having a stiffness coefficient of $k=1.5*10^6$ N/m, with no damping. Regarding the symmetry of the geometrical form of the tank it is enough to consider only ¼ of it. If just the dominant horizontal component of earthquake is considered for analysis the total roof stiffness in the main direction is obtained by the following formula:

$$= 1.5 \times 10^6 \times \sum_{\theta=0}^{90} \cos^2(\theta) = 1.472 \times 10^7 \quad \frac{N}{m}$$

$$K_{radial} = \sum_{\theta=0}^{90} k \times \cos^2(\theta) \;, \theta = 0, 5, 10, \ldots, 85 \; degrees \tag{1}$$

Using Epstein's formula (1976) for the added mass effect results in a total added mass of around 20% of the weight of the impounded oil in the tank. This is mainly corresponding to the first mode of sloshing. Since this first mode is not considered dominant in this study the amount of added mass is considered to be around 10% of the total weight of the impounded oil in the tank. For constructing the added mass matrix the lumping technique presented by Al Zein (2004) can be used. The simplified model of the tank-oil-roof system is shown in Figure 2 and the first three modes of vibration of this system is shown in Figure 3.

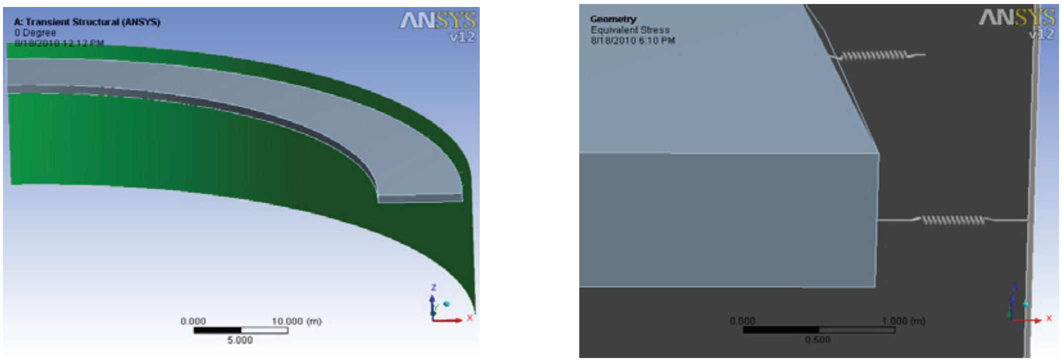


Figure 2: Modeling the tank and its floating roof by the Finite Element Program: one fourth of the tank wall and roof system (left) and the only-compression elements (right)

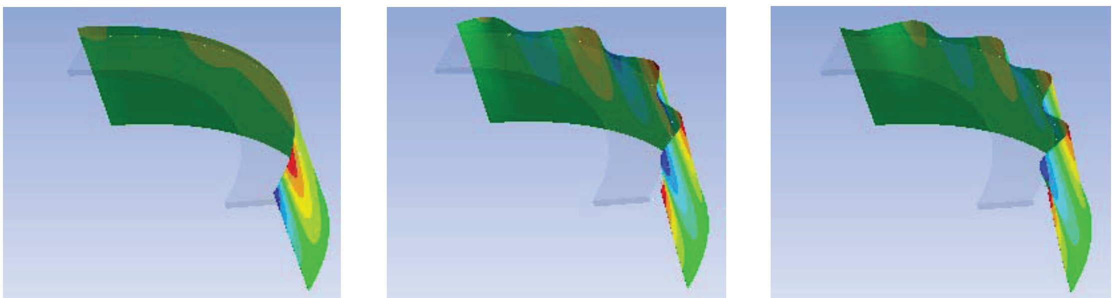
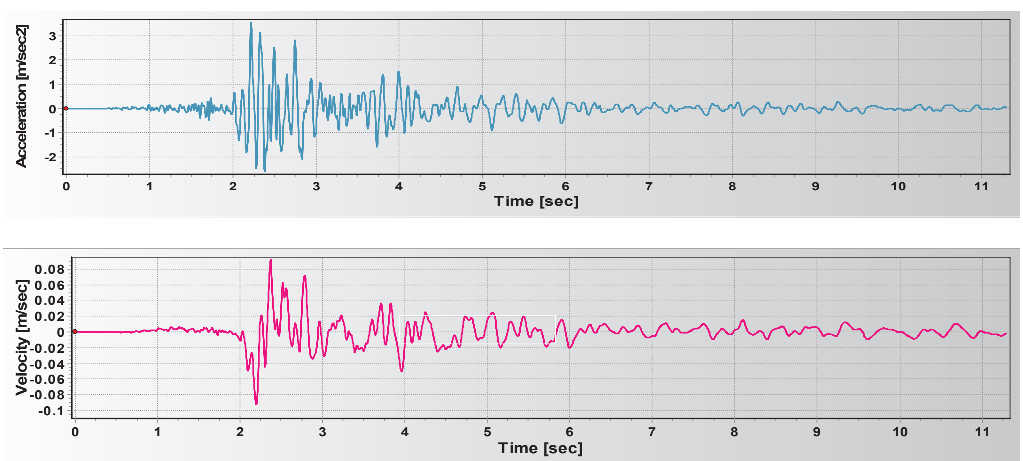


Figure 3: The modal shapes of the first (left), second (middle) and third (right) modes of the tank-oil-roof system

The natural frequencies of the first three modes of the tank-oil-roof system are respectively 0.83034, 1.8793, and 1.8975 Hz. For time history analysis (THA) of the system the strong motion part of the Doobaran, Kharg earthquake of 2003 with the time step of 0.005 sec was used. Time histories and corresponding spectra of this earthquake are shown in figure 4.



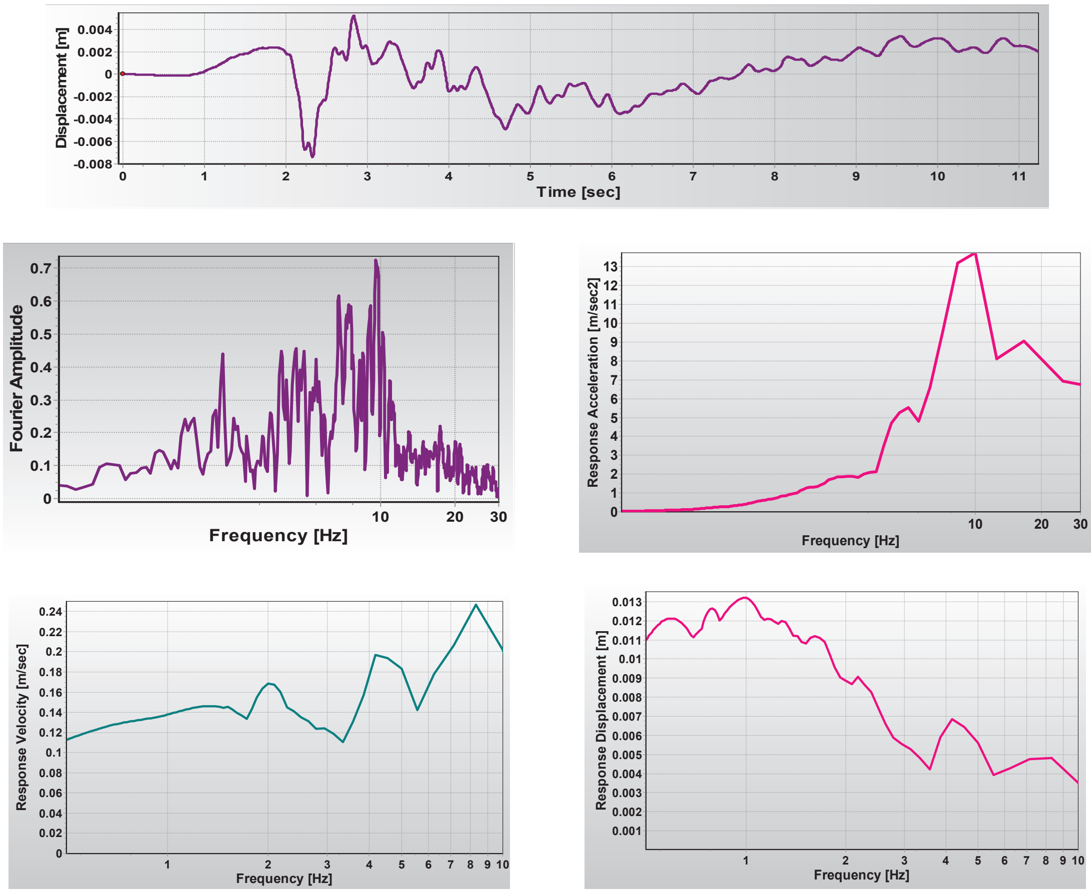


Figure 4: Acceleration, velocity, and displacement records of Doobaran earthquake of 2003 and its corresponding spectra

A sample of the THA results Figure 5 shows the response history of the relative displacement of the two ends of the only-compression element in the main direction of earthquake excitation.

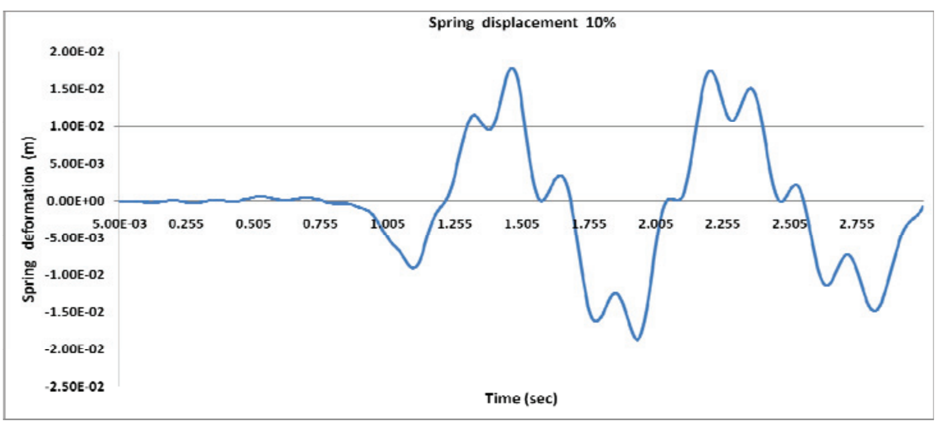


Figure 5: A sample of deformation response history of the only-compression springs

As another sample of the numerical results the von Mises stress distribution in the tank's wall is shown in Figure 6, which is corresponding to the instant of 1.33 sec.

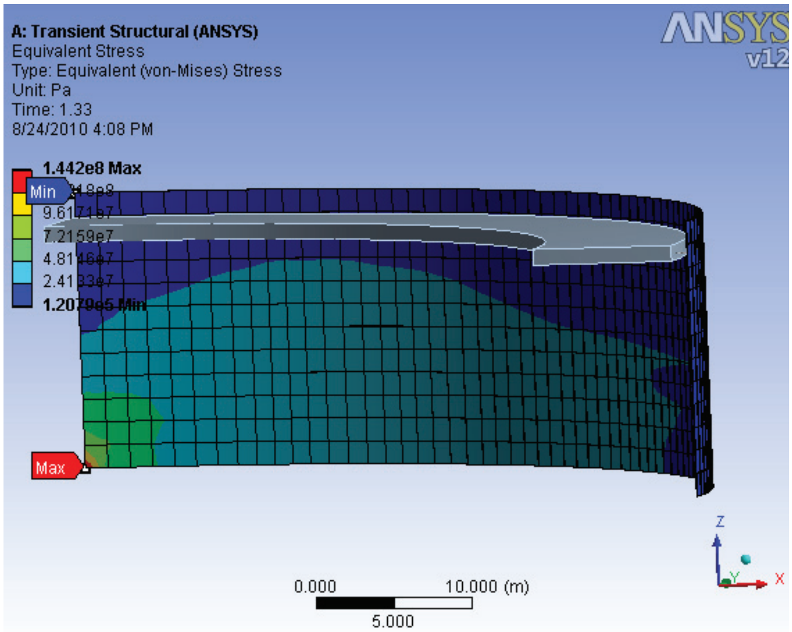


Figure 6: von Mises stress distribution in the tank's wall at the instant of 1.33 sec

The dominancy of the first mode of the tank system vibration (with the natural period of around 1.2 sec) can be seen in Figure 5. This figure also shows that the maximum deformation of the only-compression element subjected to Kharg earthquake is around 1.8 cm. If the sealing elements around the roof cannot provide this much deformation the tank system is considered vulnerable. Figure 6 shows that the maximum von-Mises stress is around 144 MPa, occurring in the lower mid part of the tank's wall. However, this value is less than the yielding stress of the steel material used in the tank's wall.

3. Conclusions

Numerical results show that for earthquakes similar to the chosen one in this study the maximum amount of deformation which the sealing element should provide to prevent separation between the seal and the tank's wall is 2 cm. As various sealing elements are used around floating roofs, more research is required to realize which kind of seal is more appropriate for this purpose. With regard to the stress values in the tank's wall as long as the fixed foundation are considered for earthquakes similar to the used earthquake in this study the wall remain elastic, however, for other types of wall to foundation connection more analyses are required.

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